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**STRESS ANALYSIS AND DAMAGE EVALUATION OF FLAWED
COMPOSITE LAMINATES BY HYBRID-NUMERICAL METHODS**

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INTRODUCTION

Structural components in flight vehicles is often inherited flaws, such as microcracks, voids, holes, and delamination. These defects will degrade structures the same as that due to damages in service, such as impact, corrosion, and erosion. It is very important to know how a structural component can be useful and survive after these flaws and damages.

To understand the behavior and limitation of these structural components researchers usually do experimental tests or theoretical analyses on structures with simulated flaws. However, neither approach has been completely successful. As Durelli states that "Seldom does one method give a complete solution, with the most efficiency."(1) Examples of this principle is seen in photomechanics which additional strain-gage testing can only average stresses at locations of high concentration. On the other hand, theoretical analyses including numerical analyses are implemented with simplified assumptions which may not reflect actual boundary conditions.

Hybrid-Numerical methods which combine photomechanics and numerical analysis have been used to correct this inefficiency since 1950's. But its application is limited until 1970's when modern computer codes became available. In recent years, researchers(2-5) have enhanced the data obtained from photoelasticity, laser speckle, holography and moire' interferometry for input of finite element analysis on metals. Nevertheless, there is only few of literature being done on composite laminates. Therefore, this research is dedicated to this highly anisotropic materials.

CLASSIC LAMINATE THEORY

Composite laminate is made of a stack of laminae in which each lamina may be laid out in a different designated orientation to take advantage of the strength of fibers. It is relatively less understood compare to metal materials. The main differences between composites and metals include non-uniformity through thickness and anisotropic constitutive law. So that the stiffness matrix of a laminate element must be built from every lamina (layer) and assembled according to some basic assumption of elasticity.

In each lamina its unidirectional reinforced fibers may be laid in a direction different from loading axes, structural axes. As it is known the mechanical properties are usually tested and given along or perpendicular to fiber orientation, material axes. Therefore, the stiffness of every lamina must be transformed into unified structural coordinates system for assembly. Consequently, its normal and shear stress-strain relation is coupled after the transformation. This special characteristic is not seen in isotropic materials.

Once the stiffness of all laminae are calculated, the loading-deformation relation of a laminate element can be obtained. In which loading includes in-plane normal/shear forces and bending/twist moments per unit length; deformation includes normal/shear strains at middle plane and bending/twist curvatures. This provides the fundamental constitutive law of composite laminates for finite element analysis.

FINITE ELEMENT ANALYSIS

Finite element method which appreciates the speed and memory size of modern supercomputer becomes very powerful in stress analysis. It use admissible approximate displacement function to estimate strain field in an element. And then stresses field is calculated with the constitutive relation of materials. So the mechanical behavior of whole structure can be defined by minimizing the potential energy and expressed as follow:

$$[K] \{q\} = \{F\} \dots\dots\dots [1]$$

where $\{q\}$ is a column matrix of all nodal displacements and rotations; $\{F\}$ is a column matrix of all input nodal forces and moments; and $[K]$ is a square symmetric stiffness matrix which is assembled with the stiffness of all elements.

Finite element method is very useful specially for structures with complex or singular boundary which can not be solved by analytical methods. Flaws in a composite laminate structure is an example of singular boundary. At those singular areas, stresses are highly concentrated and its displacements vary drastically. So that it requires much finer element to express the variation of stress and strain fields.

DIGITAL IMAGE TECHNIQUE

As it being stated early, displacement fields which can be measured accurately away from stress concentration areas, has been used as input data for finite element analysis to avoid the unknown and difficult boundary conditions in experiments or services. Displacement is measured by a digital image technique developed at the University of South Carolina(6-8). It is done by comparing two digitized images to determine the deformation between images. The system uses a standard video camera attached to a video digitizer. The digitizer transforms an image to a 512 x 512 set of numbers representing the image. Each number represents the intensity of light impinging on a small area of the camera sensor, which is referred to as a pixel. The value of each pixel ranges from 0 to 255 representing from black, different shades of gray, to white respectively. Anyway, these values are then processed by a correlation code in a computer to obtain the deformation field.

FAILURE ANALYSIS

Failure is measured with failure criteria which depend on materials. Because composite materials is interested in this study, the failure modes and failing procedure of a laminate must be understood. And then a criterion can be chosen to predict the failure of composite laminates. As it is known that a lamina can be degraded and failed under following modes: (a) matrix failure with cracks; (b) fibers failure by being broken, buckled, or kinked as a group; (c) debonding between fiber and matrix; (d) delamination between layers. These failure modes interact and occur simultaneously as well as sequentially.

With above understanding researchers have proposed some criteria to assess the failure of composite laminates. Among them, the Tsai-Wu Tensor Theory is mostly adopted for a polymer composite lamina. According to this theory a lamina will have initial crack and start to degrade if its stress state can not satisfy the following inequality:

$$F_{ij}\sigma_i\sigma_j + F_i\sigma_i < 1 \quad \dots\dots\dots [2]$$

It works nicely when delamination and buckling are not concerned. Since linear elasticity has been assumed the Strength Ratio (R), ratio of stresses at failure to the tested stresses, can be estimated by the following equation:

$$(F_{ij}\sigma_i\sigma_j) R^2 + (F_i\sigma_i) R = 1 \quad \dots\dots\dots [3]$$

This Strength Ratio can be interpreted as how many times of current loading the lamina would be started to degrade. If every laminae are degraded the loading level is referred as Last Ply Failure of laminates. In experiments acoustic events may be heard at this moment.

EXAMPLES AND RESULTS

Specimens of quasi-isotropic, [0/45/-45/90],, and cross-ply, [0₂/90₂],, laminates made of T300/F934 prepregs with 1/8 inch diameter central hole are tested with uniaxial tension. Images are taken during the tests for deformation evaluation. The area of images is about 0.77 inch long by 0.91 inch wide. Results of digital image correlation show that the values of displacement along boundary are staggering due to the inevitable error in the process. So that displacements along the boundary of this area are smoothed with the Least Square method before input in the finite element analysis. A computer code, ABAQUS, has been employed for this stress analysis(9).

For quasi-isotropic laminates an eight nodes quadrilateral shell element is used. The edge of hole is divided into 128 elements to catch the stress concentration. Stresses at

concentrate locations is then used to estimate the loading level of first lamina failure and Last Ply Failure. The result predicts that the specimen is totally degraded and its fibers may start to break when loading reaches 980 pound. It agrees very well with the observation in the test while acoustic events has been clearly heard at about 950 pound level. For the cross-ply laminates a 20-nodes solid element is used to reflect the delamination between 0 and 90 degrees laminae which has been observed in the tests. This current work will be done soon in the future, and results will be shown in the next report.

REMARK AND FUTURE WORK

The preliminary results of Hybrid-Numerical Methods has demonstrated an excellent agreement with that in the experiments. It is found that the loading capacity predicted is about an half of the value estimated by a conventional analysis. Because this more realistic approach can enhance structural designs and has the potential to predict the capacity of structures with flaws and after initial damages. It should be studied further on the composite laminates with damages such as impact, delamination, corrosion and erosion.

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